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Procedia CIRP 23 (2014) 206 – 211

www.elsevier.com/locate/procedia

Conference on Assembly Technologies and Systems

Form-Flexible Handling and Joining Technology (FormHand) for the Forming and Assembly of Limp Materials

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Abstract

The assembly of limp, elastic or differently shaped objects poses a huge challenge which needs to be met by machine tools and the corresponding processes of handling, forming and joining. These processes are often carried out manually. This technological gap triggered the present work at the Technische Universität Braunschweig. A novel form-flexible handling tool (FormHand) is presented which focuses on the automation of these production steps taking into consideration the material behavior. The combination of the flexibility of both industrial robot and the FormHand end-effector allows for new processes appropriate for these materials. This article investigates the used materials of the granular filler and the cushion textile, the working states of FormHand and the use of online sensors for an automated process application.

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Selection and peer-review under responsibility of the International Scientific Committee of 5th CATS 2014 in the person of the Conference Chair Prof. Dr. Matthias Putz matthias.putz@iwu.fraunhofer.de

Keywords: Form-Flexible Handling and Joining, Assembly, Automation, Process Design, Handling of Objects with Different Characteristics, Preforming

1. Introduction

Handling, forming and joining of limp, elastic or differently shaped objects poses a huge challenge to an automated assembly [1]. This challenge has to be met by the used machine tools and the corresponding processes.

For example, processes for the production of textile preforms or the film lamination of curved surfaces so far have been often carried out manually. In these processes the handling and joining of materials like textiles, leather or thin foils are essential. These process steps pose extreme challenges to the used production tools [1] and [2]. Firstly limp materials have to be gripped without any destruction of their surface. Secondly these materials have to be formed according to the desired geometry. Finally they have to be fixed in their final shape. The fixation itself poses a further

challenge since the accessibility to the joining area is blocked by the handling devices. Other examples are found where a huge variety of differently shaped objects are handled and assembled. Here form-flexible devices that are adjustable to the shape of each object can replace a big amount of handling tools. Usually, the mentioned production processes are automated for one product only and show drawbacks in their flexibility. For each change in geometrical dimensions or material characteristics a different handling device is required.

This technological gap triggered the present work at the Technische Universität Braunschweig to realize novel form-flexible handling and joining devices for these processes. This article presents a new concept, called FormHand, which integrates and parallelizes these production steps. FormHand features a vacuum gripper with the form-flexibility of a granular filled cushion. This combination makes it necessary

to take the material behavior into account. Further it is necessary to find control methods for an automated use of such a form-flexible device. Here, an appropriate approach that integrates material characterization, modeling of FormHand working states and an online sensor use is required. The combination of the flexibility of both industrial robot and the FormHand end-effector allows for new processes appropriate for these materials.

This article describes the FormHand concepts, reviews main characteristics of the used materials and shows an approach for process control. A demonstration process for the use of FormHand is described in the following.

2. Form-Flexible Handling and Joining Devices

The investigation on form-flexible handling tools showed that at this time no appropriate technologies are available on the market. But there are designs and prototypes of different concepts in research. All of them are currently in development. The following examples give an overview of these concepts that cope with the same challenges as FormHand. They introduce form-flexible end-effectors focusing on the handling of textiles, especially transforming or forming textiles from the plane into a three-dimensional shape.

The device described in [2] and [3] was designed at IWB, Munich, Germany. The gripper is constructed cylindrically and can be rotated around its principal axis. The surface is composed of elastic foam material and is made of several identical modules. Each module is individually equipped with valve actuators and heating elements and can be controlled separately. A connected vacuum generator creates an airflow, which generates a negative pressure inside the gripper and thus the holding force at the gripper surface. Gripping and releasing of fabrics is carried out by a rolling motion. During this movement the modules are activated and deactivated sequentially. The form-flexibility is only realized by the foam material at the surface. In this way, the surface can adapt the contour of the preform tool with limited molding depth. The flexible surface returns to its original state as soon as outer forces are withdrawn.

Another adaptive multifunctional end-effector, designed at IGM, Aachen, Germany, is described in [4]. This end-effector has discrete grasping points with mounted cryo grippers. The form-flexibility is realized by a parallelogram mechanism, which is actuated by a drive unit at the center of the gripper. Because of its kinematic structure the molding ability of this design is limited to uniaxially curved surfaces.

Other designs, such as [5], [6] and [7], realize a passive form-flexible end-effector that bases on jamming of granular material. In the most simple form the end-effector consists of an elastic air-impermeable membrane such as a latex balloon, which is filled with granular material, e.g. ground coffee. In the interior of the membrane, positive and negative pressure may be created by an external pump. If the pressure inside is negative, the granular material is slightly compressed and solidifies. This change of state is used to grip objects. The balloon like body of the gripper is pushed around the work piece in soft state. Then it is hardened. The range of items to

grip is wide, because of the high level of form-flexibility. With such a device, objects are handled by form closure only. Thus textiles can hardly be gripped.

This overview shows that most of the investigated grippers are considerably restricted in form-flexibility due to the used kinematics and geometry. Additionally, these grippers are equipped with discrete grasping points. Although standard components can be used, this limits the functionality when gripping differently shaped objects. Only one end-effector applies a grasping mechanism by an air stream that is situated homogeneously on the surface of the gripper.

3. The FormHand Concept

FormHand extends the design of the described prototypes. It recombines vacuum area grippers as e.g. described in [2-3] and the form-flexibility of non-rigid grippers [e.g. 5-7]. This allows a higher form-flexibility and higher molding depth for vacuum area grippers. It also extends the granular grippers [5-7] by implementing force closure in addition to form closure as a gripping mechanism, making it especially suitable for handling of limb objects.

The FormHand concept describes a form-flexible vacuum tool that can be used in different configurations: as a gripper, as a forming tool or as a passive form itself. This innovative concept of FormHand is ready for the integration of further functionalities, such as heating, actuation or sensor-based quality assurance, see [8], [9] and [10].

Fig. 1 shows a conceptual design of FormHand with its main parts. The form-flexible handling device consists mainly of a base frame (1) and a cushion (3). The base frame has three main functions: It acts as a mechanical interface to a robot, connects the vacuum generator and the cushion via a vacuum connector (2) and gives stability to the cushion (transmission of process force while forming) and integrates further components such as sensors, actuators or heating elements.

The gripper cushion (3) is filled with granular material (4). The form-flexibility of the cushion is limited by the mobility of the granular particles. The stiffness of the cushion can be changed with an adjustable airstream by vacuum suction via the base frame. The change in stiffness is due to the jamming of the granulate particles within the cushion. At the bottom, the cushion has a porous area, the gripping area. Here, the work piece is ingested by the airstream through the gripper cushion. This area also allocates a form-flexible heating device (5) that is used for the activation of any kind of hot-melt adhesives, see [8].

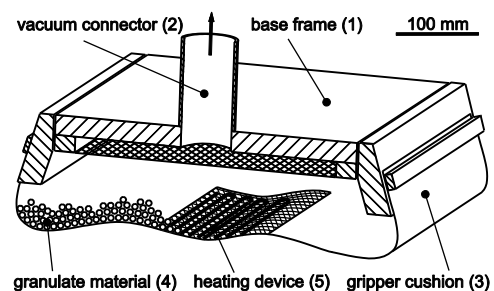


Fig. 1: Conceptual design of FormHand with its main design parts.

The design and function of FormHand indicate that this handling device is different from conventional end-effectors. There is no defined geometry of the gripper. This is due to the form-flexibility of the gripper cushion filled with granular material. Only the basic dimensions of the frame and the cushion are known. The shape of the tool may vary within the operation process between the individual sub-processes. Basically there are two main limit states of the FormHand gripper cushion:

- a *soft state*, no vacuum is applied, see Fig. 2 and
- a *hard state*, an air flow through the cushion compacts the granular filler of the cushion, see Fig. 3 and Fig. 4.

The stiffness and thus the behavior of the granules inside the end-effector may be varied during the handling process. Parameters such as the mold geometry, the properties of the gripped work piece, the applied air flow rate and applied external forces influence the stiffness behavior of the FormHand cushion significantly.

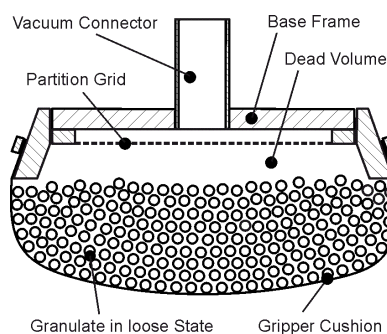


Fig. 2: FormHand in soft state. The filler is moveable freely since no vacuum is applied. No gripping forces are generated.

Responsible for the huge range of process parameters are the properties of the materials used for the end-effector, especially in the gripper cushion. Here the interplay of the textile covering and the filler lead to this particular behavior. If the packing density of the filler is increased by compression, caused by external forces or generated vacuum, yokes between the granular particles emerge and the granular material undergoes a transition from a liquid-like state (soft state) into a solid-like state (hard state). The granular material becomes compacted. This is designated as jamming phase transition and is a particular property of granules. This makes studies on the behavior of granules under stress necessary, see section 4.

In both states an airstream through the cushion can be realized. A gripping by force closure of any object at any state of the FormHand is possible. The gripped objects are mainly ingested by the air flow. Additional gripping forces are generated, as soon as the granules transfers into a compacted state. Then objects can also be fixed by form closure, see Fig. 3. Only in the hard state, FormHand can transfer specific reaction forces from the base frame of the gripper to the ingested object into the mold.

Limp materials and especially air permeable materials require a full surface contact while gripping. To achieve this,

the FormHand cushion forms onto the textile layer in soft state. The air flow ingests the textile cut-out with a very low vacuum, distributed over the whole surface, see Fig. 4. The filler becomes compacted and FormHand changes into the hard state. Through the adjustment of the air flow the cushion becomes softer again and the gripped limp object can be changed in its form by a forming tool, see Fig. 5. If the air flow increases again, the form can be kept. These abilities of FormHand can be used for an automated preforming, see [8].

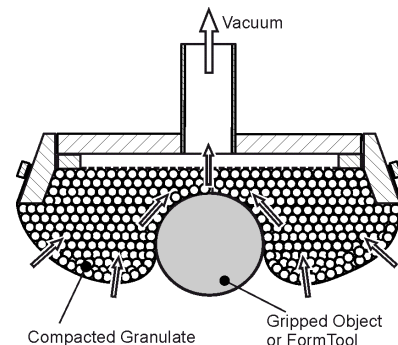


Fig. 3: Hard state of FormHand: Ingesting a round shaped object. The granular material flows in the soft state of FormHand around the object and fixes the object in the hard state also by form closure.

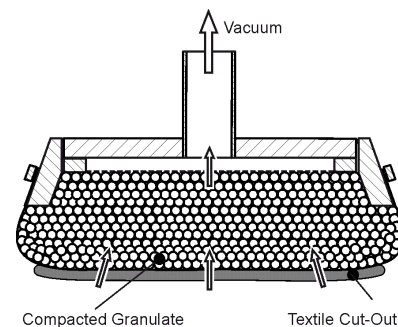


Fig. 4: Hard state of FormHand: Ingesting a flat textile object. Even air-permeable objects stick to the low pressure area vacuum gripper.

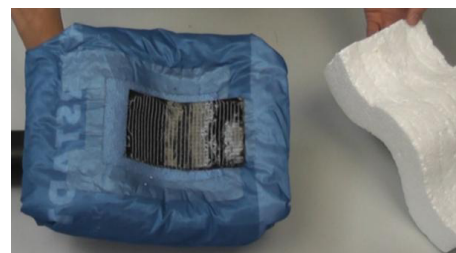


Fig. 5: Functional model of FormHand for the validation of gripping and forming of a textile material. Here FormHand is in a hard state ingesting a carbon fiber textile, after being formed by a mold (right).

4. Characterization of Granular Materials

The description of the FormHand concept makes clear that the selection of a suitable granular material is essential for an

effective use of FormHand. But further it is necessary to find control methods for an automated use of such a form-flexible device with its only roughly defined working states. The basis for the needed control methods is a deeper understanding of the described working states. This triggered an investigation with the aim to understand the general interaction of the FormHand cushion and the used filling. To achieve this aim, at first basic practical experiences with the behavior of candidate granular materials have to be gathered by the experimental characterization of these materials. Fig. 6 shows the selection of investigated granulates for these experiments.



Fig. 6: Selection of granulates (G1 to G6), from top left: EPP, EPS, expanded glass, ABS, rape seeds, cherry pits. See also [8].

One of the most important granular characteristics is the flowability of the material inside the gripper cushion. The higher the flowability, the more FormHand is able to adapt to different geometries. Three different test set-ups were used to characterize the flowability of the selected granulates:

- **Flow Time:** A certain amount of granular material flows through a cone. The time until the cone is emptied is counted. A shorter flow time means a higher flowability.
- **Angle of Movement:** Granular material is put into a drum. The drum starts to rotate until an avalanche is observed. At this point the angle θ is measured. θ describes the repose angle, also called the angle of movement of the certain granulate. A small angle of movement is an indicator for a good flowability.
- **Displacement Force:** The granular material is placed in a cylindrical container. A stamp, smaller than the diameter of the cylindrical container, pushes from the surface through the granulate to the bottom of the container. The force acting on the stamp is measured continuously. High forces indicate a low flowability.

Besides flowability, there is another important characteristic of granular materials for the use in FormHand: the reaction to compression. In order to measure the effects which occur while compressing granular materials, two tests scenarios were set up:

- **Compression (1D):** Same as in the set-up for measuring the displacement force, in this set-up the granules are compressed by a stamp (with a defined area A) within a cylindrical container. This time the stamp fits right within the walls of the container. The stamp compresses the sample with a defined speed, while the force, acting on the stamp and the surface of the material, is measured. From this measurement the mechanical behavior of the sample can be derived. Low pressures for a high displacement indicate a good compressibility or jamming of the granules.
- **Shear Test:** The shear test determines the shear strength of a granular material. Shear strength is defined as the maximal value of the shear stress before the material fails. In this test, a load σ is applied normal to the sample. Then, the material is forced to shear, while the shear stress τ is measured. Repeating the test with different normal loads allows determining the internal friction μ with $\mu = \tau / \sigma$. Granulates with a high internal friction show a better stability in the hard state of FormHand, since it is harder to shear the particles under the influence of a normal load.

In the initial experiments (flowability and reaction to compression) the best material was evaluated through direct comparison. This figured out that EPS has good characteristics for the considered application. The flowability of EPS is very high since the particles are relatively small and have a ball like shape. EPS shows a very high elastic compression which leads to a high inner friction in the hard state of FormHand. This is important to keep the shape of a formed FormHand cushion very well. For the following experiments the FormHand demonstrators will be equipped with EPS particles.

5. Sensor Control for an Automated Use of FormHand

The described properties of the FormHand concept pose a great challenge to the automated use of FormHand. At the same time these properties allow for a flexible process application of this tool, since FormHand can take care of different jobs. If FormHand is connected to an industrial robot, see Fig. 7, there is no information on the exact geometry of the gripper.

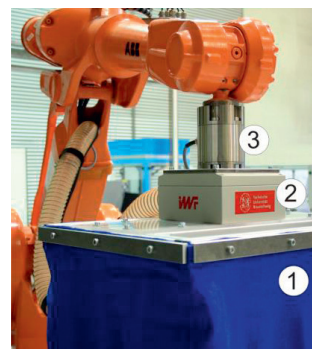


Fig. 7: FormHand (1) mounted to a six DOF industrial robot with connected vacuum supply (2) and force-torque sensor (3). Approx. gripper area of this FormHand module at the bottom: 300 x 210 mm²

This is due to the form-flexibility and the non-Newtonian properties of the granules inside the gripper cushion. This makes it necessary to find models that describe the FormHand behavior during its use. These models base on the one hand on the characteristics of the used materials, see above. On the other hand they use process data acquired by sensors, as described in the following.

A first approach for the creation of the required models is the integration of a force-torque (FT)-sensor as an interface between end-effector and the robot hand, see Fig. 7. By means of the FT-sensor the contact forces between FormHand and the molding tool shall be monitored continuously during the whole process. Additionally, a flow rate sensor is used to monitor the actual air flow through the gripper cushion. The aim is to use the recorded sensor data for process control and to connect these data with the FormHand characterization of offline investigations. The experiments with the described set-up focus on two aspects: Firstly, the state of the gripper is to be controlled in dependence of the occurring forces and torques. Secondly, the sensor data is used as input for controlling the end-effector pose to compensate occurring torques.

The stiffness and deformation behavior of FormHand at increasing forces was investigated by means of a force-distance test with the FT sensor. For this purpose, the form-flexible end-effector was mounted with the FT-sensor on a six-axis robot. This way the end-effector was moved with low constant velocity along a linear path onto a plane mold (movement along the z-axis). The movement was stopped when reaching a defined maximum force. During the movement, the distance and the resulting contact forces were recorded. In addition, the deformation behavior of the cushion was observed. The experiment was performed at different pressure differences, respectively air flow rates.

Fig. 8 visualizes the collected data from a characteristic run of the force in Z-direction in a force-distance-diagram. The curve is not linear. Initially, it has a flat slope, which becomes increasingly steeper with increasing distance. During this phase the cushion of FormHand is deformed by redistribution or displacement of the granules inside the cushion. The cushion is soft and adapts the shape of the contact surface. At a certain point, the slope of the force curve is constant until it reaches the maximum force. The force progresses linearly. This corresponds with the result from the material characterization of the EPS granules. EPS was used for the build-up of the investigated FormHand demonstrator.

It is observed that the gripper cushion shows no further deformation. Granules are not redistributed anymore and the cushion is in the hard state. Further deformation and adaption of the surface is not possible. Only the elastic deformation of the individual particles leads to small changes in shape of FormHand. With variation of the vacuum inside the cushion, the transition takes place at higher differential pressures rather than at lower. Fig. 9 depicts the actual transition of the gripper cushion, according to the data from Fig. 8.

The time at which the non-linear force curve changes to linear is the phase transition of the jamming. The granules in the cushion change from its fluid-like state (soft state) to the solid-like (hard state). The observed linear curve reflects Hooke's law and represents a value of the granules' elastic

behavior. At low pressure differences, this state is reached when the volume of the cushion is equivalent to the volume of the granules while FormHand is molded. With increasing pressure differences, the phase transition occurs earlier, because the cushion is pressed harder on the granules by the vacuum.

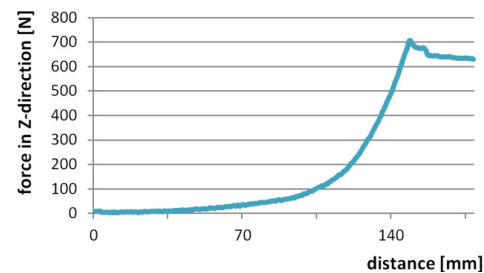


Fig. 8: Force applied on the FormHand cushion depending on movement in Z-direction. Correlation to the characterization of EPS material.



Fig. 9: Test scenario of FormHand with sensor integration. Left: Cushion in soft state, right: the cushion is compacted to a maximum (hard state).

The transition has implications for the use of the form-flexibility in the forming process. The adaptation to a mold can only be done during the first phase, in which the granular particles flow past each other. Once the granules partially or throughout the cushion are compacted, further deformation and adaption is not possible. Only in this state forces can be transmitted from the base frame into the mold.

6. Demonstration Process with FormHand

The investigations from section 4 and 5 illustrate the described properties of FormHand. The results obtained will be used below in an exemplary forming process. For this purpose a demo process was developed, in which the form-flexibility is used and the stiffness behavior is monitored by the installed sensors. This demo process is derived from the requirements of an automated preforming process. It consists of three steps: gripping a fabric, transporting the fabric and forming/draping the fabric into a mold, see Fig. 10.

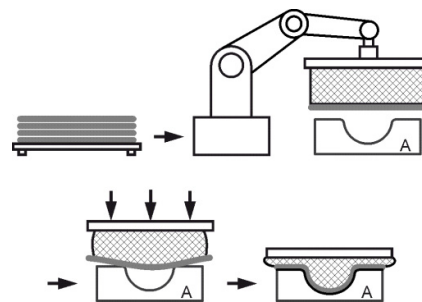


Fig. 10: Test Scenario for FormHand.

In the first process step, the fabric is stored on a plane surface area. The form-flexible end-effector moves in parallel position with the base plate onto the fabric and grips it by means of the air flow. In the second step the fabric is transported to a mold. The third step is the actual forming. The FormHand slowly moves with the gripped fabric into the mold and presses it like a punch against the contour. During the entire process flow, the sensor data from the FT- and the airflow sensor are monitored.

The demo process is run twice. During the first run a taught-in-path is traversed. The sensor data of the FT-sensor initially are not included in the control of cushion status. In the second run, the monitored sensor data are used to control the shape and status of the FormHand cushion.

The force-time curves of both runs begin with the lifting of the fabric, see Fig. 11. While moving the fabric, the force in Z-direction is nearly constant. When the end-effector moves into the mold, the force of the first forming pass (see Fig. 11 a)) shows that the force between the FormHand cushion and the mold results in fast rising contact forces. After a short deformation (non linear part), the stiffness of FormHand increases and forces the robot to stop. The maximum force is achieved before the fabric has been completely pressed against the contour of the mold. Comparing the data of the FT-sensor with the observed deformation behavior of the cushion, the reason for the forces and torques become obvious: placing the FormHand into the mold leads to contact points between both objects and the formation of yokes in the granulate and thus to a local stiffening of the cushion. The granulate inside can no longer flow freely. A bead is formed, which prevents further molding. Forces are introduced locally at the contact surfaces. The forming may not be completed.

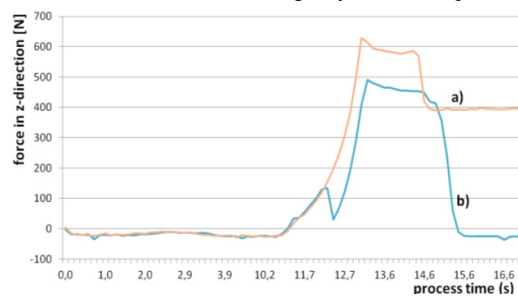


Fig. 11: Force distribution during the FormHand demo process: a) without and b) with sensor control.

In the second run, the findings of the material characterization are applied. In order to fully adapt the contour of the mold, the FormHand cushion must remain form-flexible (in the soft state) as long as possible. This means that the granular material must be kept within its flowability. Preliminary experiments have shown that this can be achieved by a lower vacuum inside the cushion. Therefore, in the second run (Fig. 11 b)), the state of FormHand is controlled in dependence of the forces and moments measured by the FT-sensor and the air flow rate sensor.

If contact forces, which can lead to an early stiffening of the cushion, are registered while moving FormHand into the mold, the differential pressure in the cushion is reduced to

allow further deformation of FormHand. The peak in the process run shows that the contact force in the Z-direction decreases immediately after decreasing the differential pressure. In this state further deformation of the cushion is possible. FormHand can be moved deeper into the mold as in the first run. This way the forming of the textile can be finalized.

7. Conclusions and Outlook

This article described a novel handling and joining device, called FormHand. FormHand features a vacuum gripper with the form-flexibility of a granular filled cushion. The combination of the flexibility of an industrial robot and the FormHand end-effector allows for new processes, for example for an automated preforming. But from this combination arise different challenges for the automated use of such a device. Especially the non-Newtonian behavior of the gripper cushion makes it necessary to find control methods. To find appropriate methods, this article investigated the used materials, the working states of FormHand and the use of online sensors. The developed control methods were validated in a demonstration process.

The presented work shows the potential of FormHand. With the integration of further functionalities FormHand can be used for the automation of a wide range of processes. This will require a deeper understanding of the behavior of the FormHand cushion. The here presented methods build the basis for more sophisticated models of FormHand.

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